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# Experimental Study of the Behavior of Steel Structures Protected by Different Intumescent Coatings and Exposed to Various Fire Scenarios

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## ABSTRACT

Three different experimental setups corresponding to three different fire scenarios were used to investigate how different heating conditions and heating rates affect the behavior of two different thin intumescent coatings (solvent-based and water-based paints, respectively). The results confirm that the current procedure for the design of intumescent coatings has shortcomings, as different paints have different performances according to the heating conditions and, in particular, according to the fire's heating rate. The tested water-based paint had better performance for low heating rates, while the tested solvent–based paint had better performance for high heating rates. However, for really low heating rates the solvent-based paint did not activate or provide proper insulation.

## INTRODUCTION

Thin intumescent coatings have become the dominant passive fire protection system used to protect structural steel from fire [1]. These coatings swell on heating to form a highly insulating foamed char, hence preventing steel from reaching critical temperatures that could cause structural failure. The increasing growth of intumescent coatings in the built environment is associated with the low impact in the attractive appearance of bare steel structure, with their ability to be applied off site, and with their potential for offshore applications [1]. Intumescent coatings are thermally reactive fire protection materials and they are usually composed of a combination of organic and inorganic components bound together in a polymer matrix [2, 3].

Current design procedures for assessing the amount (i.e. thickness) of intumescent coating needed to protect steel profiles exposed to fire are based on standard fire tests, in particular the cellulosic standard fire curve [4, 5]. However, several studies have highlighted that the behavior of intumescent coatings not only depends on the temperature, but it can be highly influenced by other conditions of any given fire event, for example the heating rate [2, 3, 6, 7]. As a consequence, the current design procedures used for intumescent coatings are fundamentally based on the standard fire exposure, and hence cannot be

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applied to other fire conditions due to the fire-dependent nature of these organic fire protection materials. Therefore, the standard fire exposure does not necessarily replicate the worst-case scenario.

In the literature several research studies have proposed various approaches and methodologies to analyze the performance of intumescent coatings exposed to different fire conditions. Anderson et al. [8] developed a one-dimensional model to evaluate the effective thermal conductivity of the intumescent char. Li et al. [2] proposed a simple approach to assess the equivalent thermal resistance of intumescent coatings subjected to the ISO834 cellulosic fire [4]. Dai et al. [9] carried out some experiments on steel joints partially protected by intumescent coatings and subjected to standard fires. Wang et al. [3] performed some furnace tests on steel plates coated by intumescent paints and exposed to non-standard fire curves. Still, despite the process made in these studies, the performance of intumescent coatings subjected to different fire scenarios is still not fully understood due to the complexity of the intumescing process and the huge variety of different products and possible fire conditions.

The insulation properties and behavior of intumescent coatings exposed to eight different fire conditions were studied. Steel samples coated by two commercial intumescent paints were tested in three different experimental set-ups, representing different types of heating exposure. The current study highlights the limits of the current design methodology and provides some suggestions for a safer design method accounting for the various parameters that affect the intumescent coatings insulating performance, such as the heating rate and heating conditions.

## EXPERIMENTAL INVESTIGATIONS

Two different types of samples were used throughout the project. In the first and second sets of experiments, the test specimens were 400mm-long sections of standard IPE400 steel profiles, with a resulting section factor $A_s/V_s$ equal to 175 $m^{-1}$. In the third set of experiments, the test specimens were carbon steel plates of size 100 mm by 100 mm and having a thickness of 10 mm, with a resulting section factor $A_s/V_s$ equal to 100 $m^{-1}$. All the samples were painted with either a solvent-based (Paint A) or a water-based (Paint B). Both commercially available paints were professionally applied to a dry film thickness (DFT) of approximately 1 mm.

In the first set of experiments, intumescent coatings were tested in an electric oven with internal dimensions of the heating chamber of 72x82x97 cm. One IPE400 steel profile sample per test was placed in horizontal position at half distance along the main axes of the oven. The steel samples were exposed to different non-standard fire curves with heating rates lower than the ISO834 standard fire curve [4]. The four temperature-time curves were characterized by different durations and heating rates, but similar target temperatures (900-1000°C). They were qualitatively denoted as “fast”, “medium”, “slow” and “very slow”, according to the heating rates. A total of thirteen experiments (four "very slow", three "slow", two "medium" and four "fast" – six with Paint A and seven with Paint B) were conducted [11, 12].

In the second set of experiments, the IPE400 steel profile specimens were tested in a gas furnace with internal dimensions of the heating chamber of 150x150x150 cm. The furnace temperature was monitored by eight plate thermocouples placed throughout the heating chamber and it can be controlled

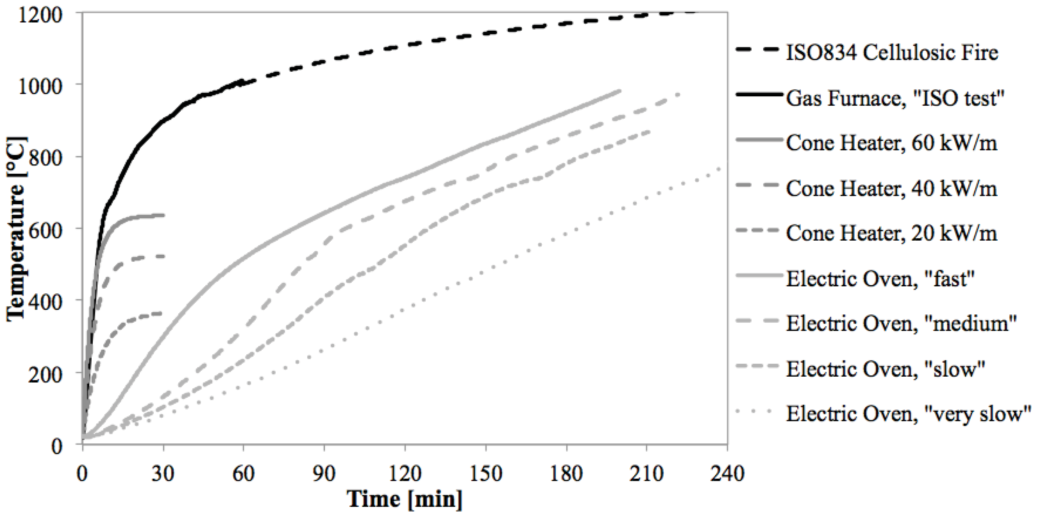


Figure 1: Unprotected steel temperature curves for all the different experimental set-up and the corresponding fire scenarios

both manually and automatically. Five steel profile samples in horizontal position (one unprotected, two coated by Paint A and two by Paint B) were tested at the same time, placed in a symmetrical configuration. The steel samples were exposed to the ISO834 cellulosic standard fire curve [4] and the test lasted 60 minutes, reaching a final temperature of 1000°C [11, 12].

In the third set of experiments, the intumescent coatings were tested in a cone heater, where a steel spiral located in the cone above the sample generated incident irradiance up to 100 kW/m$^2$. The distance between the bottom surface of the cone heater and the upper surface of the samples was set equal to 60 ± 1 mm, according to the standard ISO 5660 for dimensionally unstable materials [13]. The back of the steel plate was in contact with a layer of 20 mm thick mineral wool to minimize heat loss to the surrounding environment. The coated steel plates were exposed to different incident irradiances (20, 40, 60 kW/m$^2$) that provided temperature-time curves with heating rates similar to the ISO834 standard fire curve [4] for 30 minutes [11, 12].

In each experiment several thermocouples (NiCr-Ni, 1.4 mm, type K) were inserted into the steel specimens through holes and fixed using droplets of ceramic glue. Two to five thermocouples were placed into the each steel specimen in order to monitor the temperature distributions at different locations; thermocouples were also placed inside the heating chamber in order to control and evaluate the electric oven or the gas furnace temperature [11, 12].

Figure 1 shows the unprotected steel temperature curves for all the fire exposures implemented in the three different experimental set-ups. Each of the eight temperature-time curves is characterized by a different duration, heating rate and amount of energy provided to the steel specimens. In particular, one can observe the strong similarity between the initial branch of the temperature-time curves in the cone heater and the gas furnace tests.

## INSULATING PERFORMANCE ASSESSMENT

The insulating performance of the intumescent coatings was assessed by considering two different parameters that evaluate the ability of this passive fire protection system to prevent or reduce the heat penetration.

The first parameter is the thermal resistance $R(t)$[m$^2$K/W] of the paint. Using an analogy with dry insulation, this value can be preliminary evaluated at each time interval by using the steel heating formula from EN1993-1-2 [14] for insulated steel sections and it can be defined as:

$$R(t) = \frac{d_p(t)}{\lambda_p(t)} = \frac{1}{\rho_s c_s} \frac{T_g - T_s}{\Delta T_s} \frac{A_s}{V_s} \Delta t \tag{1}$$

where $d_p(t)$[m] is the intumescent coating thickness, $\lambda_p(t)$[W/mK] is the intumescent paint thermal conductivity, $\rho_s c_s$[J/m$^3$K] is the volumetric specific heat of the steel, $T_g$[K] is the average fire temperature, $T_s$[K] is the average steel temperature, $A_s/V_s$[m$^{-1}$] is the steel section factor and $\Delta t$[s] is the time increment.

The second parameter estimates the ability of this passive fire protection system to lower the temperature of the coated samples $T_{s,prot}$[K] with respect to the temperature of unprotected steel specimens $T_{s,unpr}$[K]. The intumescent coating efficiency $\eta_p$[-] can be defined as:

$$\eta_p = \frac{T_{s,unpr} - T_{s,prot}}{T_{s,unpr}} \tag{2}$$

## RESULTS AND DISCUSSION

The first results were obtained by evaluating the thermal resistance of the intumescent coatings according to equation (1), which enables assessment of the effectiveness of the fire protection material throughout the entire fire scenario. By collecting all the values, a common trend was observed for both the two intumescent paints in all the electric oven and gas furnace experiments. As suggested by Andersen [15], the thermal resistance curve (Fig. 2) was divided into four phases, identified according to four critical points.

The activation point marks the beginning of the intumescent chemical process and the paint swelling. It also represents the end of the inert phase, phase in which the coating is slowly melting and increasing its viscosity. In order to have a univocal definition of phase, the activation point was conventionally identified as the minimum value of the thermal resistance before the intumescent reaction. The next phase, the transient phase, is composed of a

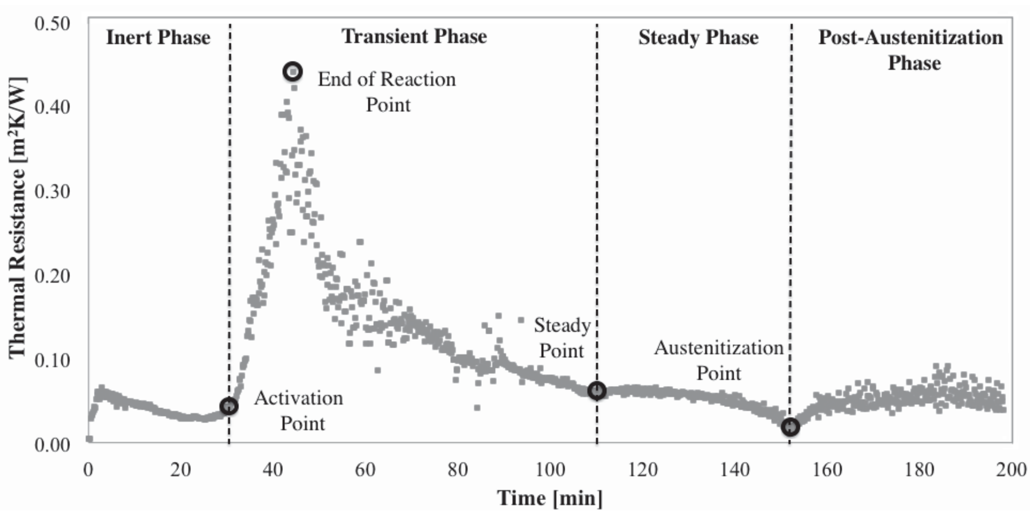


Figure 2: General trend of the thermal resistance of intumescent coatings and definition of the four general phases in its development, identified according to the four critical points

growing branch and a declining branch. In the first part, the paint starts swelling and increasing its volume. The chemical reaction stops in correspondence of the end of reaction point, which marks the thermal resistance peak. At this point the intumescent char has reached the maximum expansion and the highest insulating properties. Afterwards, the gradual decline of the thermal resistance is due to the gradual consumption of the carbon binder, the main component responsible for the cohesion and dark color of the char structure. When all combustibles have been burned, the thermal resistance reaches a steady value, which is approximately kept constant during the steady phase. The beginning of this phase, called steady point, was conventionally identified as the point of maximum curvature of the hypothetical trend curve of the thermal resistance values during the steady phase and the decreasing branch of the transient phase. Finally, the austenitization point refers to a particular phenomenon which takes place in steel at about 730°C-735°C [10]. At this temperature a molecular transformation of the steel occurs and the thermal capacity of steel increase due to this endothermic transformation. After this point the so-called post-austenitization phase starts: the carbon binder is completely combusted and, as a consequence, the intumescent char is white and very brittle. Moreover, the cracks begin to occur and they slowly decrease the insulating properties of the char structure.

Figures 3 (Paint A) and 4 (Paint B) show the thermal resistance development of the two intumescent coatings subjected to two different heating rates. The general trend with the four phases can be easily recognized in all the curves for both paints and all the five heating rates. However, it was found that the water-based Paint B had better insulating properties than the solvent-based Paint A, something which is also highlighted by the different scales of the vertical axes. Furthermore, the two paints have an opposite behavior with respect to the heating rates: the water-based Paint B has higher values of the thermal resistance at low heating rates, while the solvent-based Paint A is more efficient at high heating rates and does not activate properly for very slow heating rates.

As a conclusion, the current procedure for the design of intumescent coatings has certain limitations, as different paints have different performances according to the composition and the fire scenario. Nevertheless, the two intumescent coatings were designed according to the same standard exposure. However, according to the results obtained during this research study, this exposure characterized by really high heating rates produced the worst scenario for the solvent-based Paint B's insulating performance and, therefore, the best design case. On the contrary, the standard fire curve represented the best scenario for the solvent-based Paint A's insulating performance and, as a result, Paint A thermal resistance turned out as overestimated, representing a mistaken design on the non-conservative side.

In contrast to the electric oven and the gas furnace experiments, the cone heater experimental set-up did not allow for measurements of the intumescent coating's surface temperature, and thus the thermal resistance was not also obtainable. As a consequence, in this case the paint effectiveness was related to the intumescent coating efficiency (2). In general, similar considerations to the thermal resistance results can be also drawn from the paint efficiency developments. However, the two parameters are basically defined in a different way and they represent two slightly different aspects of the same problem. In particular, it was confirmed that the water-based paint usually has better insulation properties than the solvent-based paint. Moreover, both the paints have an increasing efficiency with increasing heat fluxes and their performances

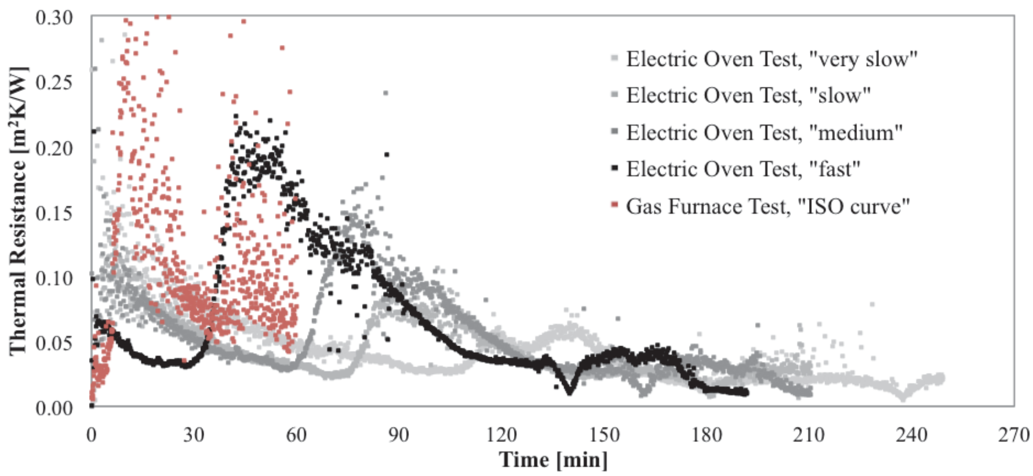


Figure 3: Paint A - thermal resistance developments for five different fire curves (electric oven and gas furnace)

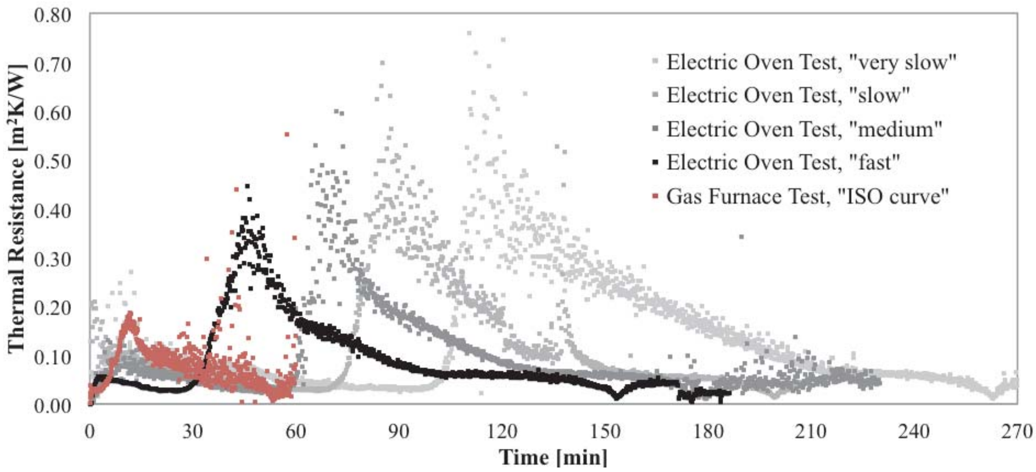


Figure 4: Paint B - thermal resistance developments for five different fire curves (electric oven and gas furnace)

become similar to each other with increasing heat fluxes (i.e. heating rates), similarly to the thermal resistance case.

Figure 5 shows all efficiencies curves for both paints for all the cases of the three different fire scenarios. As seen, Paint B had higher efficiency values than Paint A in the electric oven set-up, while for a higher heating rate in the gas furnace, Paint A's performance was better than Paint B's. However, this statement was not verified by the efficiency curves corresponding to similar fire curves in the gas furnace and the cone heater experimental set-ups. The heating rates in these two fire scenarios were really similar, as shown in Fig. 1. It should be noted that for the same heating rate, Paint A had a better performance than Paint B in the gas furnace set-up, while Paint B was always more efficient than Paint A in the cone heater experiments. The main reason of this difference may be related to the different natures of the two fire exposures. Moreover, it underlined the influence of the heating rate on the performances of Paint A and Paint B. Once again, the graph shows that Paint A had lower efficiency values at low heating rates. In particular, Paint A did not have an evident activation at low heating rates, as the maximum efficiency value within the transient phase is lower than the corresponding value for the virgin paint layer.

Finally, the maximum intumescent coating efficiency values were collected and compared for the three different experimental set-ups. Figure 6 shows the influence of the heating rate on the maximum paint efficiency value.

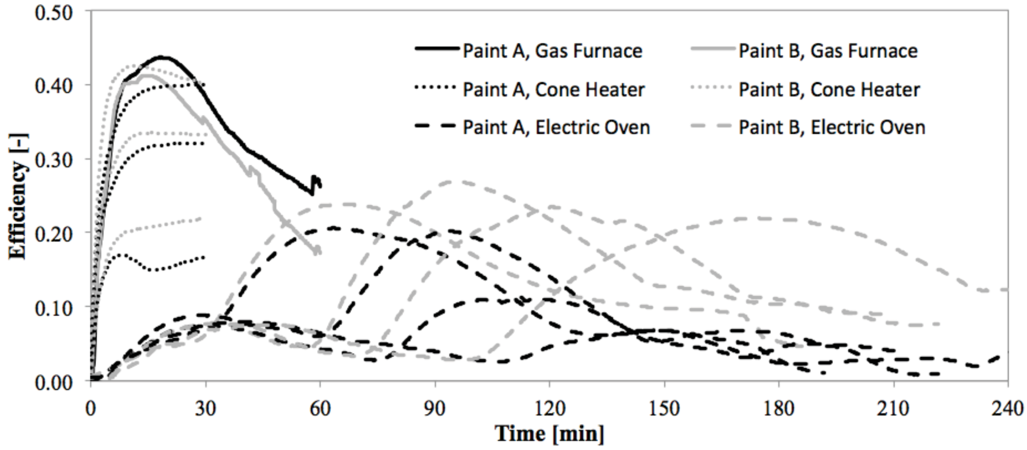


Figure 5: Intumescent coatings efficiencies for the three different experimental set-ups

Moreover, the maximum efficiency values of Paint A and Paint B were compared to the theoretical efficiency of a 1 mm non-reactive paint coating (estimated equal to 0.08). The results highlighted that the maximum efficiency values of the two coatings increased with increasing heating rates, but each of the intumescent paints had a different sensitivity to low heating rates. Regarding Paint B, its performance decreased gradually with decreasing heating rates and the paint developed good insulating properties also at really low heating rates. On the contrary, Paint A's performance decreased fast with decreasing heating rates. In particular, at really low heating rates the paint did not activate and expand at all: the maximum efficiency value is lower than the theoretical efficiency of the non-reactive paint layer. Therefore, the exposure of Paint A to slow fires leads to a degradation procedure.

## CONCLUSION

Results from an experimental study on the insulation properties of two different intumescent coatings (a solvent-based and a water-based paint) exposed to eight different standard and non-standard fire conditions showed clear differences between the two paints and highlighted the importance of the heating rates when assessing the performance of intumescent paints. The insulating performance of the tested intumescent coatings was assessed by considering the variation of thermal resistance. Its development followed a

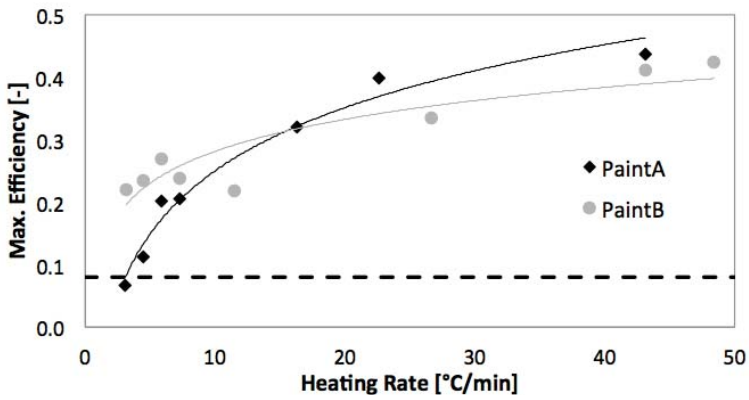


Figure 6: Influence of the heating rate on the maximum efficiency of Paint A and Paint B intumescent coating for all the three experimental set-ups, compared to the theoretical efficiency of the 1 mm non-reactive paint layer (black dashed line)

certain trend that can be divided into four general phases, identified according to four critical points on the thermal resistance curve. In addition, it was confirmed that the current procedure for the design of intumescent coatings has certain shortcomings, as different paints have different performances according to the heating conditions. In particular, different products have different sensitivity to the fire heating rates: the tested water-based paint had better performances at low heating rates, while the tested solvent-based paint had better performances at high heating rates and at really low heating rates the paint does not activate and provide insulation at all. Further studies are needed in order to confirm or contradict the exposed theories to the huge variety of different products and possible fire conditions.

## ACKWNOWLEDGEMENTS

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